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Venting Propellant Gases to Obtain Nonlethal Projectile Velocity

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Army Research Laboratory

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Abstract

Reducing muzzle velocities by variable venting of a gun barrel, thereby decreasing lethality, was investigated. Simulation was performed with an interior ballistics code (IBRGA) that was modified to have venting capabilities. Comparison of the code output with a classical solution yielded good agreement. Simulation of an M16A2 rifle showed that venting might reduce the muzzle velocity to nonlethal values if venting could commence earlier than is possible with the present M855 round. To obtain data for comparison, M16 barrels were modified to be ventable by drilling pluggable holes in the barrel at given axial intervals. Venting propellant gas from the M16 barrels yielded data that agreed with simulation results for the lower venting areas but exhibited less agreement for high area venting. Further studies are planned using a .50-caliber barrel and round, with modifications of both the weapon and the round.

ACKNOWLEDGMENTS

We thank Mr. Fred Robbins, who supplied the basic interior ballistics code and who familiarized us with the code, and we thank Mr. Andrew Brant, who advised us about the data packages for the M16A2 rifle. The final manuscript was much improved by the suggestions of Mr. David Webb.

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VENTING PROPELLANT GASES TO OBTAIN NONLETHAL PROJECTILE VELOCITY

1. INTRODUCTION

The Army has been tasked to restore law and order in other countries with a minimum loss of life and injury, which often requires the use of nonlethal weapons. Because they may encounter deadly force in such situations, the troops must also carry their standard weapons. The logistics would be much improved if a single weapon could perform both lethal and nonlethal functions.

The M16A2 rifle is the standard firearm issued to troops. To render the weapon nonlethal or lethal with a simple switch, modifications could be made in either the round or the rifle. The round's charge weight can be reduced, but such modification requires stocking yet another round because a round's charge weight cannot be changed quickly or easily. Additionally, repeatable muzzle velocities are difficult to obtain for these low charge weights. The large standard deviation in muzzle velocity is caused by the in-bore pressure being highly sensitive to the initial conditions, such as the initial spatial distribution of the propellant in the cartridge chamber. Clearly, another approach must be used to reduce the muzzle velocity.

It is proposed that propellant gas be vented from ports in the gun tube into the open air or routed back into the barrel in front of the projectile. Venting will reduce the pressure, thereby reducing the acceleration of the projectile and its muzzle velocity. Prior treatments show that venting through a constant area to the exterior of the gun is equivalent to reducing the charge (Hunt 1951). When venting occurs throughout the burning process and when the vent area is large, the muzzle velocity varies greatly with small changes in the vent areas. However, introduction of additional venting parameters, such as delaying the venting until the projectile has traveled a given distance, increasing or decreasing the venting area with distance traveled, or routing the venting around to the front of the projectile, may produce a more consistent and controlled muzzle velocity.

This report presents the computed results obtained from an IBRGA code modified to vent gases from the barrel at a chosen location. IBRGA (Robbins and Raab 1988), the basic code, is based on a lumped parameter mathematical model of interior ballistics adopted by The Technical Cooperation Program (TTCP). IBRGA also permits the use of a gradient equation that more accurately considers the chambrage of the gun (Robbins, Anderson, and Gough 1990). Here, chambrage refers to the difference in the projectile diameter and the

diameter of the case holding the propellant for the round. To validate the modified code, the results for a simulated 120-mm tank gun will be compared with the classical solution of Corner (1947). In addition, IBRGA is modified to treat dented rolled ball propellant, which is used in the rounds fired by the M16A2 rifle. Experiments are performed with this weapon and the results are then compared with the simulated results.

2. THE VENTING INTERIOR BALLISTICS EQUATIONS

The interior ballistics equations used in IBRGA are discussed in some detail by Robbins and Raab (1988). In particular, the equation governing the linear acceleration, \dot{v}_p , of the projectile is given as

$$\dot{v}_p = \frac{A(P_b - r_b - P_g)}{m_p} \quad (1)$$

in which A is the area of the bore, P_b is the pressure on the base of the projectile. The variable, r_b , is the bore resistance attributable to friction and engraving, P_g is the pressure of the gas or air ahead of the projectile, and m_p is the mass of the projectile. The base pressure usually depends weakly on whether the chambrage or the Lagrange model is used (Robbins and Raab 1988).

Venting will modify the in-bore gas pressure and will usually reduce the acceleration on the projectile over at least the first part of its in-bore trajectory. In the IBRGA model, the pressure depends on many quantities, some of which depend upon the mass of the gas. These quantities that are involved in the calculation of the in-bore pressure are all vented along with the mass. The convected quantities are the burned mass of propellant, the total energy in the propellant gas, the mass integral of the impetus divided by the flame temperature over the volume of the propellant, the mass integral over the co-volume, and the mass integral over the impetus divided by the specific heat ratio minus one. These values are all needed to obtain the pressure, which determines the burning rate, and so forth. It is assumed that the burning propellant grains are not convected with the vented propellant gas even though it is known that some propellant grains will be convected out the vent hole.

The vented rate of change of a quantity is integrated in parallel with the other quantities by a Runge-Kutta method. It is assumed that the quantity being vented is uniformly distributed in the propellant gas and is convected with the vented mass. These integrated quantities are then subtracted from the values that are obtained without venting to obtain the corrected values. These corrected values then give the correct force on the projectile and the correct burning rate for the propellant. The averaged specific heat ratio can also be calculated. The accuracy of the quantities obtained depends upon the accuracy of obtaining

the mass flux, \dot{C} , that is venting. For instance, for the energy venting,

$$\dot{E} = \frac{E\dot{C}}{C}, \quad (2)$$

in which E is the mean total internal energy of the burned fraction of propellant plus the energy of the propellant gas attributable to its forward motion in the tube. The overdot above the symbol designates the derivative of that symbol with respect to the time. The other quantities, other than the mass flux for the propellant gases, are obtained in the same way. The expression for the mass flux is obtained with Ratau's co-volume corrections for $\gamma = 1.25$, in which γ is the ratio of the specific heats. This expression is

$$\dot{C} = [(\psi P A_v)/\sqrt{RT}](1 - 0.224\epsilon + 0.104\epsilon^2), \quad (3)$$

in which A_v is the vent area, R is the average value of the gas constant per unit mass for the remaining gas, and T is the average value for the temperature of the remaining gas. Also,

$$\psi = \sqrt{\gamma} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{2(\gamma-1)}}. \quad (4)$$

The quantity ϵ depends on the average value of the propellant gas co-volume, b , and also ρ , which is the average density of the combusted gas remaining in-bore, in the following way:

$$\epsilon = b\rho/(1 - b\rho). \quad (5)$$

Equation(3) has been obtained using the correct value of γ , except for the small co-volume corrections that assume $\gamma = 1.25$. The maximum value of ϵ for the 120-mm problem discussed below is approximately 0.01 and for the M16A2 rifle problem, the maximum value would be $\epsilon \approx 0.003$. A more accurate approximation for the co-volume correction would not seem to be in order.

A subroutine was added to IBRGA for controlling the venting in a simple way. The venting area, A_v , given as the fraction of the bore length traveled, x , is

$$A_v = a_o A H(x - x_o), \quad (6)$$

in which A is the bore area, $H(x - x_o)$ is the Heaviside step function so that H has the value 1 for $x > x_o$ but has the value zero otherwise, and a_o is a constant or initial fraction of the bore area being vented.

IBRGA was also modified to handle dethered rolled ball propellant. The rolled ball grains were approximated as concentric shells in which the burning rate and force per unit mass

changed linearly between the outside and the inside surface of each shell. All these changes were made without changing the file input format, although it was necessary to change the interactive format.

3. WEAPON PARAMETERS USED FOR VALIDATION AND SIMULATION

Weapon parameters were first needed to validate the modified IBRGA code. The 120-mm cannon was used since its propellant characteristics approximated the parameters for the classical problem and solution of Corner (1947).

The M16A2 rifle and ammunition are readily available to perform venting experiments, but the current version of IBRGA cannot address the deterred propellant used in the ammunition. The IBRGA code was further modified to handle the deterred propellant so that the simulation results could be compared with the data.

3.1 120-mm Cannon

IBRGA, modified with venting capabilities, was compared with the classical solution obtained by Corner (1947). The propellant, projectile, and gun barrel length are all non-standard.

The parameters used in the venting comparison were

Gun parameters

Bore diameter	120 mm
Bore volume	9180 cm ³
Travel	6.304 m
Igniter propellant mass	0.19 kg
Propellant mass	8.05 kg
Projectile mass	2.657 kg

Igniter characteristics

Impetus	0.589 MJ/kg
Co-volume	.948 cm ³ /g
Gamma	1.22

Flame temperature	2562 K
Density	1660 kg/m ³
Burning rate	0.1 m/s
Perforations	1

Propellant characteristics

Impetus	1.153 MJ/kg
Co-volume	.948 cm ³ /g
Gamma	1.23
Flame temperature	3447 K
Density	1580 kg/m ³
Burning rate	1.225 P ^{0.961} mm/s, P < 41.38 MPa (P is in MPa)
Burning rate	1.322 P ^{0.941} mm/s, P < 700 MPa
Perforations	15

3.2 M16A2 Rifle

Next, the interior ballistics for the M16A2 rifle were simulated. The results of some of these simulations can be compared with experiments performed with a vented M16 barrel. Some gun and ammunition parameters supplied by Mr. Frederick Robbins are as follow:

Bore diameter	5.56 mm
Bore and chamber volume	13.14 cm ³
Travel	.467 m
Igniter propellant mass	0.00454 g
Propellant mass	1.75 g
Projectile mass	3.37 g

Deterred rolled ball propellant is used for the standard M16 rounds. The original propellant is formed into uniform spheres and treated chemically to reduce the impetus, the flame temperature, and the burning rate of the outer regions of the grain. The deterring chemical is absorbed so that the propellant properties vary in a continuous manner. The grains are then flattened into a pancake shape. The chemical treatment and the rolling combine to create a grain that, before processing, was digressive but is now decidedly progressive. These

properties can be modeled as a function of the distance burned into the grain. Specifically, the grain consists of concentric shells with different properties at the outer surface of each concentric shell. The properties between the outer and inner surfaces of the shell are found by linear interpolation. The shell designations along with their associated properties are shown in Table 1.

Table 1. Propellant Characteristics, Round for M16A2

No.	d_f mm	F MJ/kg	T K	b cm^3/g	γ	Mass g	ρ g/cm^3	β $\text{mm}/\text{s}/\text{MPa}^\alpha$	α
1	0.342	0.658	1700	1.13	1.31	0.108	1.534	0.861	0.71
2	0.329	0.852	2250	1.08	1.27	0.144	1.534	1.077	0.76
3	0.313	0.971	2800	1.04	1.25	0.250	1.534	1.382	0.81
4	0.281	1.115	3380	.983	1.23	1.247	1.534	1.817	0.86

The column labeled " d_f " is the distance between the flats of the given shell. The rolled ball propellant grains can be thought of as consisting of a disk with the outer part of a toroid affixed to the outside of the disk. The greatest length of this particular rolled ball propellant is 0.8 mm before burning. The grain is assumed to burn uniformly everywhere on its surface.

The round just described is no longer easily procurable but simulations are performed to indicate what might be possible. Venting experiments are performed with the M855 round, which is commercially available. Some of its properties are as follow:

Igniter propellant mass	0.00454 g
Propellant mass	1.67 g
Projectile mass	4.018 g

The number identification of each shell along with its defining size, d_f , and surface characteristics are shown in Table 2. The diameter of the unburnt grain is 0.841 mm.

4. CODE VALIDATION AND SIMULATIONS

4.1 120-mm Cannon

One would expect venting to lower the in-bore pressure throughout most of the projectile's in-bore travel and reduce the muzzle velocity. To confirm these expected results and compare

Table 2. Propellant Characteristics, M855 Round for M16A2

No.	d_f mm	F MJ/kg	T K	b cm ³ /g	γ	Mass g	ρ g/cm ³	β mm/s/MPa ^a	α
1	0.270	0.658	1700	1.13	1.31	0.092	1.534	0.861	0.71
2	0.260	0.852	2250	1.08	1.27	0.123	1.534	1.077	0.76
3	0.247	0.971	2800	1.04	1.25	0.218	1.534	1.382	0.81
4	0.221	1.115	3380	.983	1.23	1.247	1.237	1.817	0.86

with available theory, calculations are performed for a 120-mm cannon when it is not venting and when it vents with $A_v/A = 0.1$. The calculated pressure at the base of the projectile as a function of time is shown in Figure 1 for both nonvented and vented firings. The vented gun has a higher pressure at later times although the vented gun's base pressure is always lower when compared as a function of the projectile's travel distance.

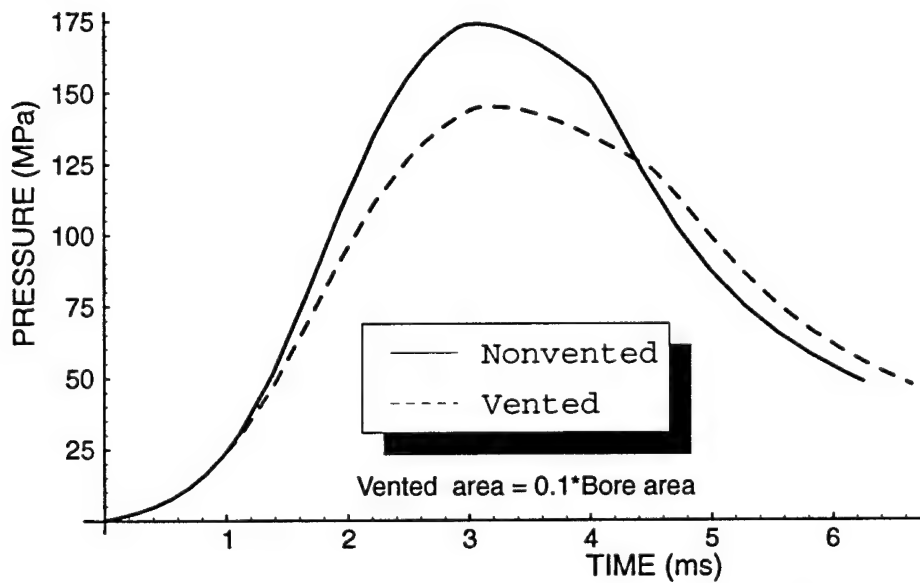


Figure 1. Nonventing and Venting Comparison for the Pressure at the Base of the Projectile (for 120-mm cannon in which $A_v = 0.1$).

These calculated results can be used to compare with results obtained from Corner's (1947) approach. The interior ballistics parameters used do not completely comply with Corner's problem, as posed. Corner assumes a propellant in which the rate of burning is proportional to the pressure, while the 120-mm propellant has a burning rate that is almost proportional to the pressure. Corner also makes other assumptions that would be expected

to yield some agreement with accurate detailed solutions. For instance, Corner assumes a space- and time-averaged constant value, $\lambda = \overline{RT}$, in the analysis. Corner's analysis shows that the venting gun gives the same results as the nonventing gun but with a smaller charge mass and a more digressive grain geometry. His analysis yields the dimensionless parameter, Ψ , which is used to calculate the reduced muzzle velocity and peak mean pressure in the bore volume,

$$\Psi = \frac{\psi A_v D}{\beta C \sqrt{\lambda}}, \quad (7)$$

in which D is the web size for the calculation.

It is established (Corner 1947) that the leaking gun muzzle velocity, V_{pv} , varies from the nonleaking muzzle velocity, V_p , as $1 - n\Psi$. Likewise, the peak pressure varies as $1 - 2n\Psi$. Following Corner (1947), $n \approx 0.7$ and using a rough estimate, $\sqrt{\lambda} \approx 1,000$ m/s, it is calculated that $\Psi \approx 0.104$ for the leaking gun. The comparison with Corner's (1947) solution results applied to the 120-mm cannon is shown in Table 3. For the assumptions made by Corner, these results are in good agreement, especially considering that these velocities are higher than the range of velocities addressed in 1947.

Table 3. Comparison of Peak Mean Pressure and Muzzle Velocity, Numerical and Analytical Calculations (simulation of 120-mm cannon [$A_v/A = 0.1$]).

Quantities $n = 0.7$	Corner (1947) Leaking Gun	Modified IBRGA Leaking Gun	IBRGA
V_p (m/s)	2,017	2,034	2,175
P_{peak} (MPa)	264	269	333

4.2 M16A2 Rifle Simulations

Calculations were run for the M16A2 rifle with the first set of conditions referred to earlier. Calculations for the nonventing case were first compared with results obtained with the IBHVG2 code (Anderson and Fickie 1987). The pressure and projectile velocities agreed almost exactly and the insignificant differences were attributed to the use of the chambrage gradient model instead of the Lagrange gradient model used by the IBHVG2 code. Figure 2 shows a comparison of the muzzle velocities obtained as a function of vent area with the parameter x_o , which is the fractional distance that the projectile travels before venting

occurs. For the curve in which $x_o = 0.0$, or in which venting occurs upon initiation of travel, Figure 2 shows that the muzzle velocity increases with the vent area in a small region. This increase is caused by the progressive nature of the propellant coupled with a very small travel distance. Here, the projectile travels a very small distance when the slower burning layer is burned, exposing a faster burning layer. In the small space available, the fast burning propellant layer can increase the gas pressure and thus, the muzzle velocity. Of course, with further increase of vent area, the pressure decreases more rapidly, which reduces the burning rate.

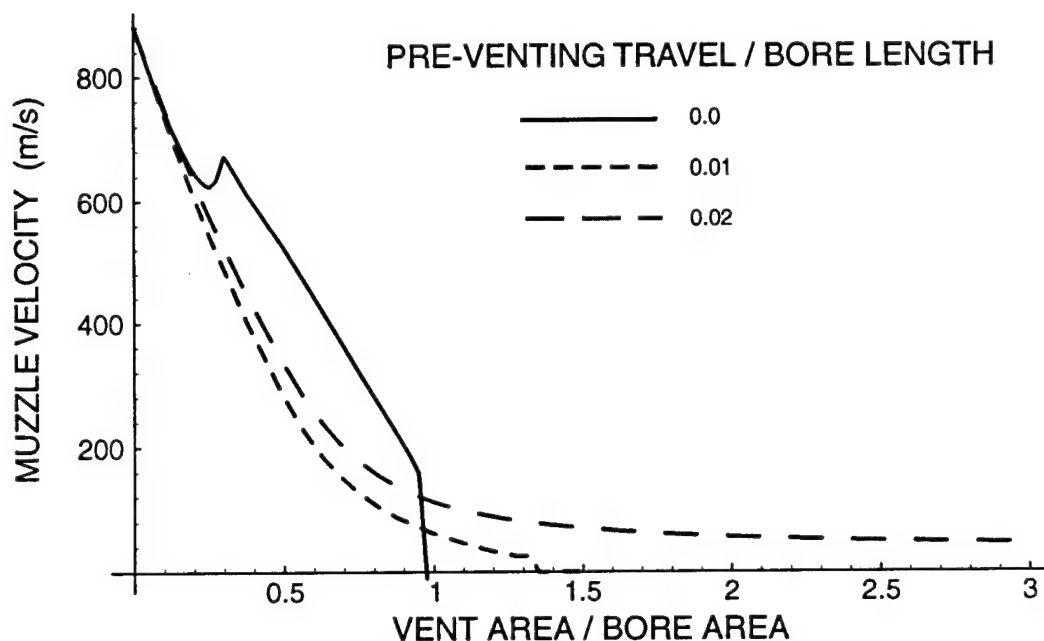


Figure 2. M16A2 Velocity Versus Vent Area with Parameter x_o (characteristics supplied by Robbins).

Figure 2 shows that, for low muzzle velocities, the muzzle velocity sensitivity with vent area depends strongly on the value of the pre-venting travel fraction, x_o . For the highest value of x_o shown, the muzzle velocity varies little with the bore area. In contrast, when venting is started immediately, very small changes in any conditions such as vent area or propellant characteristics will cause the muzzle velocity to vary rapidly at the lower muzzle velocities. Thus, delay of venting appears to be an attractive strategy and should be pursued in more detail.

Calculations were performed over a large range of venting areas and pre-venting travel fractions to examine the resulting muzzle behavior. Figure 3 shows muzzle velocity contours as a function of vent area and pre-venting travel fraction for the M16A2 with the first set of rolled ball propellant characteristics. The velocity contour lines are bunched together for

the lower values of the pre-venting travel fraction. The contour lines then spread apart for the higher values of x_o . At these parameter values, large changes in vent area result in only small changes in muzzle velocity, and the prospects of good repeatability are increased. These larger values of pre-venting travel present an attractive region for experimental explorations.

Although the results using the first set of propellant parameters are encouraging, the particular round simulated in Figure 3 is not immediately available. The M855 round is now the most available ammunition, but the rear of the M855 projectile occupies approximately 3/8 inch of the front part of its cartridge case, so that the pre-venting travel fraction for this round must be greater than 0.03. Figure 3 indicates that the most favorable pre-venting distance might be between 0.01 and 0.02 of the total in-bore projectile travel. Because the parameters for the M855 propellant are similar to the parameters for the M16 round just discussed, the optimum pre-venting distances for the M855 round to achieve nonlethal velocities should be similar.

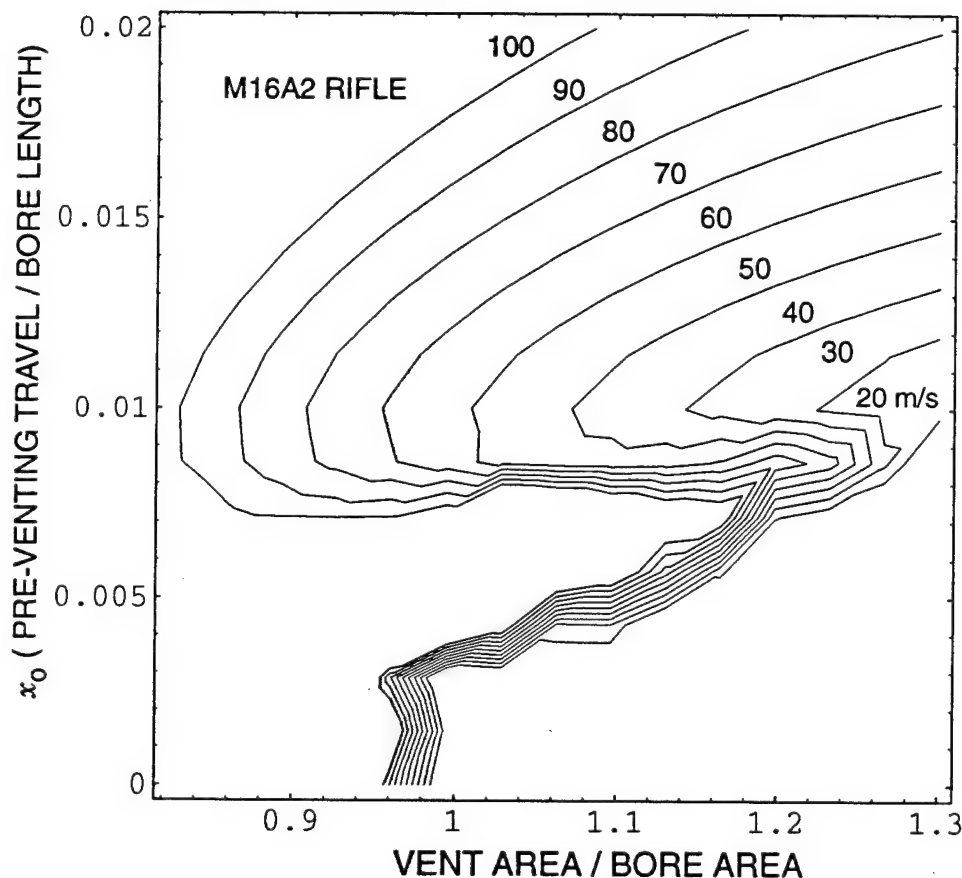


Figure 3. Velocity Contours (m/s) as a Function of Vent Area and x_o (calculations for M16A2 rifle).

5. VENTING EXPERIMENTS AND COMPARISONS WITH SIMULATIONS

Since M16A2 rifle barrel blanks and ammunition were available, the decision was made to modify these barrels to vent at positions along the length of the barrel. Most of the interior ballistics parameters are also well known and allow comparison between experiment and simulation. Two barrels were modified by drilling several vent holes, which were then tapped to allow plugging of the vents with size 5-40 machine screws for Barrel No. 1 and size 10-32 screws for Barrel No. 2. One of the barrels, designated as Barrel No. 2, had additional holes drilled approximately 29 calibers (6.5 in.) to the front of the rear holes. The barrel was fitted with a sleeve that sealed the barrel in the back of the rear vent holes and another seal located in front of the front vent holes. The front vent holes were drilled to investigate the possibility that the propellant gas might enter into the barrel in front of the traveling projectile, thus exerting a force that would reduce its velocity. A drawing of Barrel No. 2 with its sleeve attached is shown in Figure 4. Near the rear of the sleeve are three rows of four threaded holes each (one row cannot be seen in the cross section), which can be opened or plugged with screws. The sleeveless barrel was designated as Barrel No. 1. The holes that are open are given by row order starting from the row nearest the breech. For instance, "4,2,0" would mean that four holes of the rearmost row were open, two holes were open in the next row, and no holes were open in the third row. If the last three row positions for Barrel No. 2 are not mentioned, that implies that the three front rows of holes are closed.

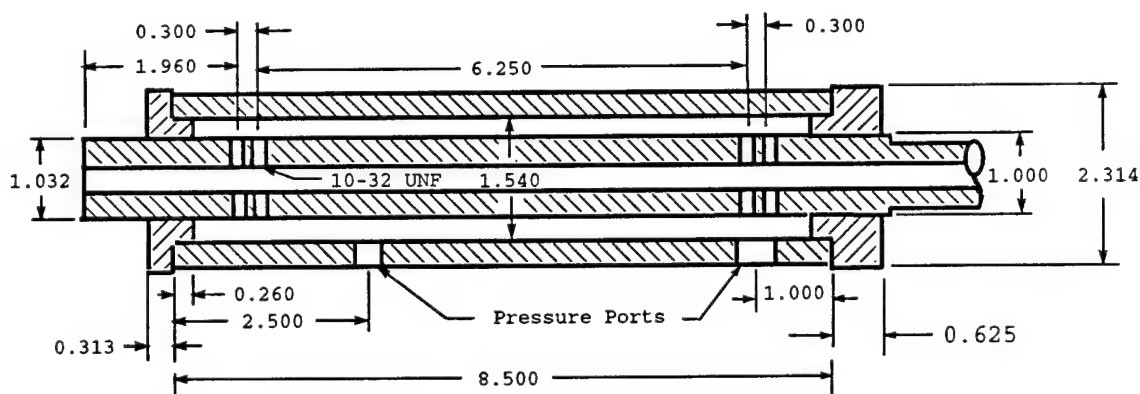


Figure 4. Drawing of Vented Barrel with Sleeve (units are in inches).

The M855 round fired from an M16A2 venting rifle was simulated with the modified IBRGA code. The muzzle velocity contours are shown in Figure 5. The range of pre-venting starting values and vent areas for these muzzle velocity contours span some of the values used in experiments with vented M16 barrels. For a given vent area, the muzzle velocities for

the M855 round are higher than for the previous M16 round discussed. Also, the propellant for the M855 round burns more rapidly resulting in a higher maximum chamber pressure than for the previous propellant formulation.

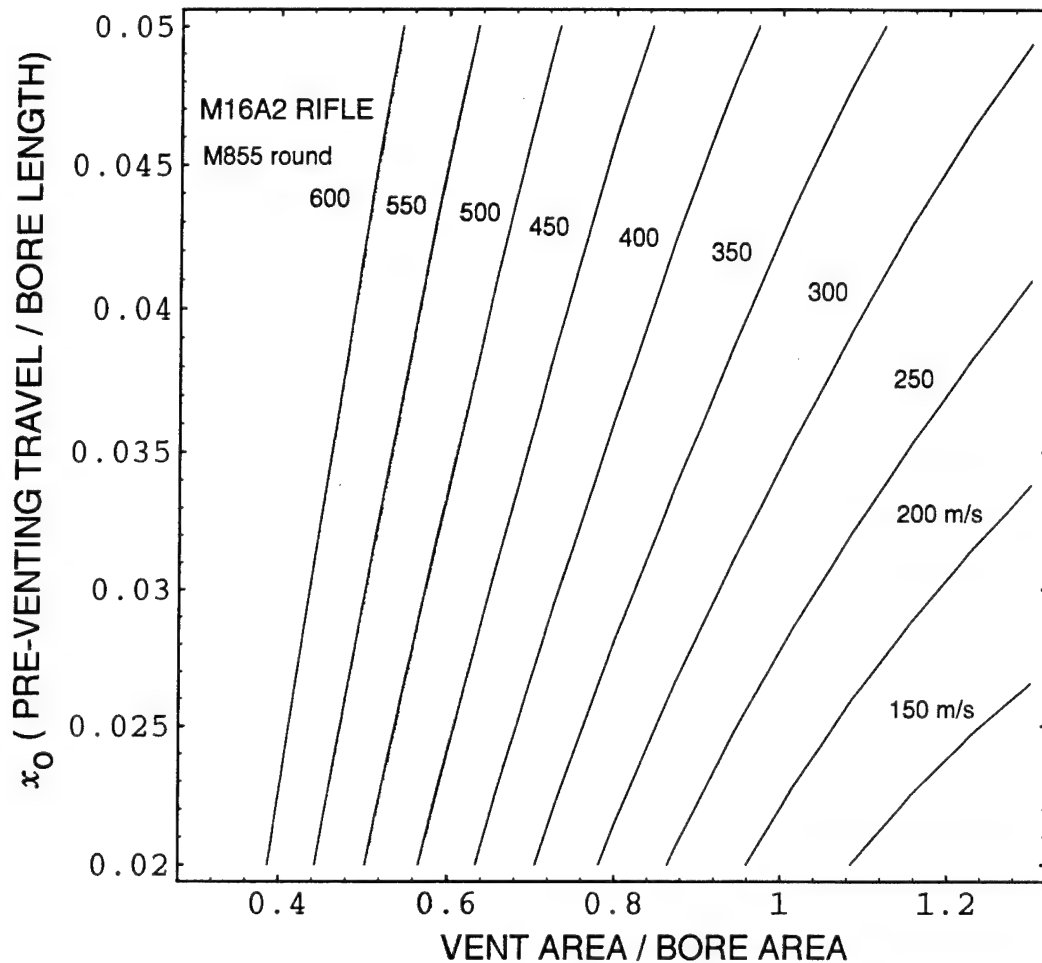


Figure 5. Muzzle Velocity Contours (m/s) for M855 Round with Vented Barrel.

The first barrel was fired in various open hole configurations as shown in Figure 6. The vent hole size for Barrel No. 1 is 0.259 cm (0.102 in.). The discharge coefficient for flow through the holes was estimated as 0.8. Also shown with the results are two simulation results obtained from Figure 5. These discrete simulation results are shown by the circle symbols. Doubling the vent area, which occurs when two more screws are removed in the first position of the 2,0,0 configuration, results in the 4,0,0 configuration. The calculated muzzle velocity for the 2,0,0 configuration is larger than obtained for the experiment, while the calculated velocity values for the 4,0,0 configuration are smaller than the experimental value. From these two points, the value of 0.8 for the discharge coefficient would appear to be

a good approximation. The increase in venting obtained by going from the 4,2,0 configuration to the 4,4,0 configuration results in only a small decrease in velocity. Opening two more holes in the 0,4,4 configuration to obtain the 2,4,4 configuration results in a more marked decrease in velocity. These results qualitatively agree with the calculations, although with two or three rows of holes being open simultaneously, one cannot generate a good estimate of the equivalent pre-venting travel.

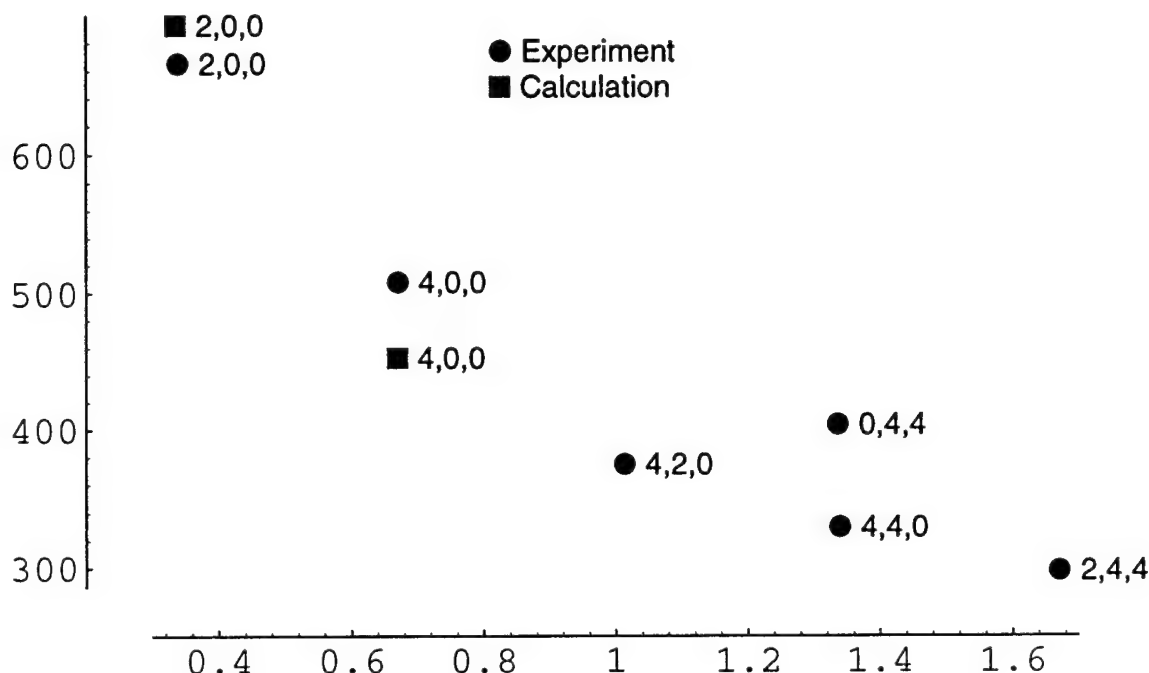


Figure 6. Muzzle Velocities for the Vented Barrel No. 1.

In agreement with the calculations, venting holes located nearer the front of the ammunition casing result in a greater muzzle velocity reduction than when holes are opened farther from the breech.

Experiments were also conducted with the vented barrel (Barrel No. 2) that could optionally be fitted with a containing sleeve discussed earlier. Again, square symbols show the results of calculation, with circle symbols showing the results of experiment. The resultant muzzle velocities, during different venting conditions, are shown in Figure 7. These muzzle velocities were obtained with the sleeve off. The presence or absence of the sleeve while firing only affected the results minimally, if at all. Also, opening the set of vents near the front of the cylinder sleeve did not seem to affect the measured muzzle velocities. The results in Figure 7 were obtained with the holes being enlarged to a minor diameter of 0.381 cm (0.150 in.). The velocity for configuration 2,0,0 was somewhat higher than for the configuration

4,0,0. The calculated velocity values for the configurations 2,0,0 and 0,0,2 are much lower than those observed. The calculated values obtained with four holes open for both the 4,0,0 and the 0,0,4 configurations are so much lower than those measured that the scale of the graph would have to be increased considerably to include the simulated results. The interior ballistics lumped parameters approach is not accurately modeling the experiment for these larger vent areas, and further experiments are needed to determine muzzle velocities for the larger vent areas. A more accurate detailed picture of the venting flow might be obtained with a finite difference code.

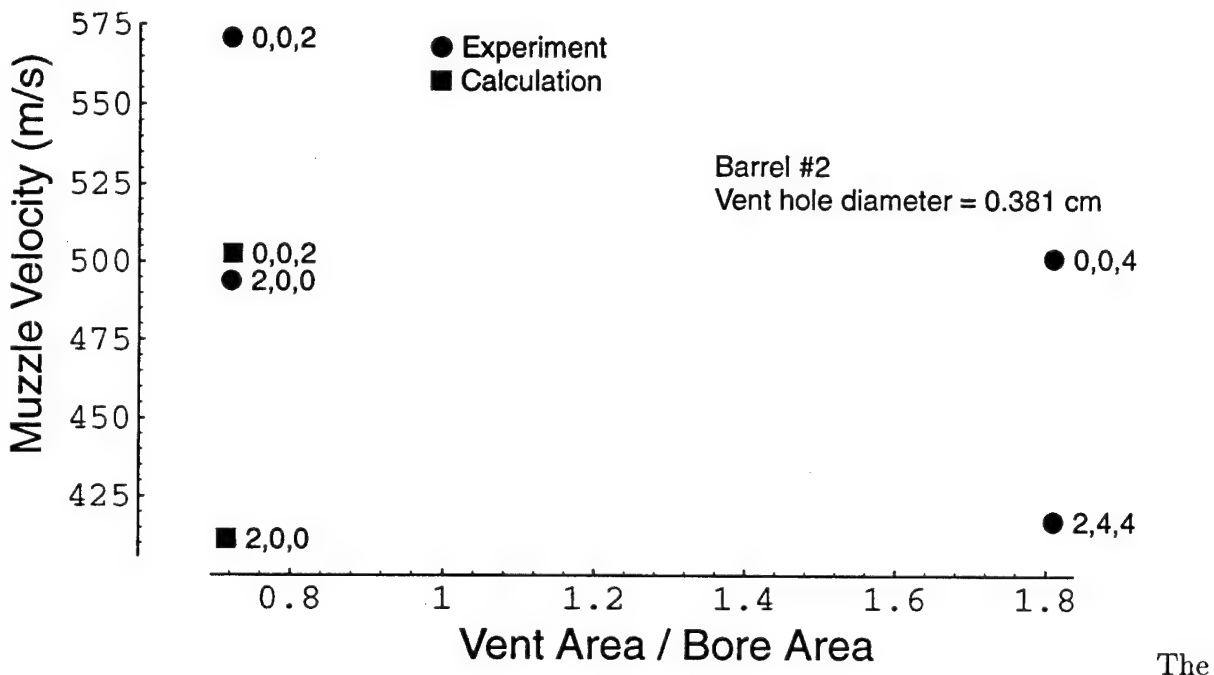


Figure 7. Muzzle Velocities for the Vented Barrel No. 2.

pressures in the sleeve cylinder were measured during the firings, and the simulation program was further modified to calculate pressures in the sleeve cylinder during the firings. The venting flow into the sleeve cylinder was assumed to be choked with the chamber pressure modeled as a one-dimensional solution of the time-dependent equations of state, mass, and energy conservation for the propellant gas (Huseman 1984). In addition, a model for the heat transfer is also implemented. Figure 8 shows a comparison of both the measured and calculated overpressure values for the rear gauge position with the 2,0,0 configuration. The peaks and valleys for the overpressure data result from the fluid movements and shock waves reflected from the ends of the sleeve cylinder. The calculation yields a monotonic pressure increase, even with a heat transfer model that should overestimate the heat losses, while the pressure data show that the pressure is declining. The pressure gauges may be receiving enough heat energy to depress their pressure sensitivity. Simulation for the 4,0,0

configuration shows that the quantity of gas vented should quickly lower the gas pressure in the barrel so that choked flow cannot always be assumed. The model does not currently address unchoked flow.

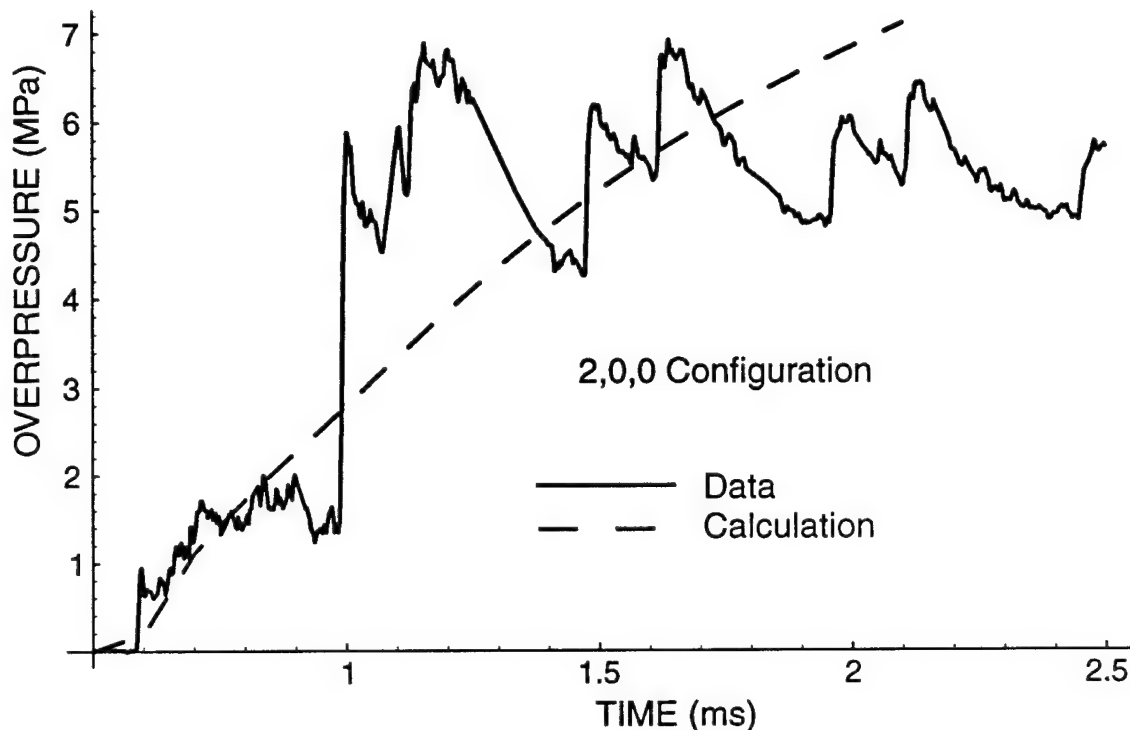


Figure 8. Overpressure Comparisons When Two Rearmost Vent Holes are Opened.

Figure 8 shows the rise of the pressure inside the chamber. This pressure increase can be interpreted with the aid of Figure 9, in which the travel fraction and the projectile velocity in the bore are shown also as a function of time. The projectile clears the muzzle in 1.6 ms after the rear set of holes are opened. The projectile passes the front set of holes approximately a half millisecond after it passes the rear set of holes. If the front set of holes are opened, they can vent for only a half millisecond with a cylinder-sleeve pressure that averages to less than a tenth of the chamber pressure for most of the time for transit. During this time, the overpressure declines from approximately 100 MPa to approximately 40 MPa. Furthermore, the pressure is unrestrained in the front of the projectile, allowing the gas to drive a shock down the tube in front of the projectile and relax to an even lower pressure in front of the projectile. These expected low pressure levels will not decrease the projectile velocity significantly.

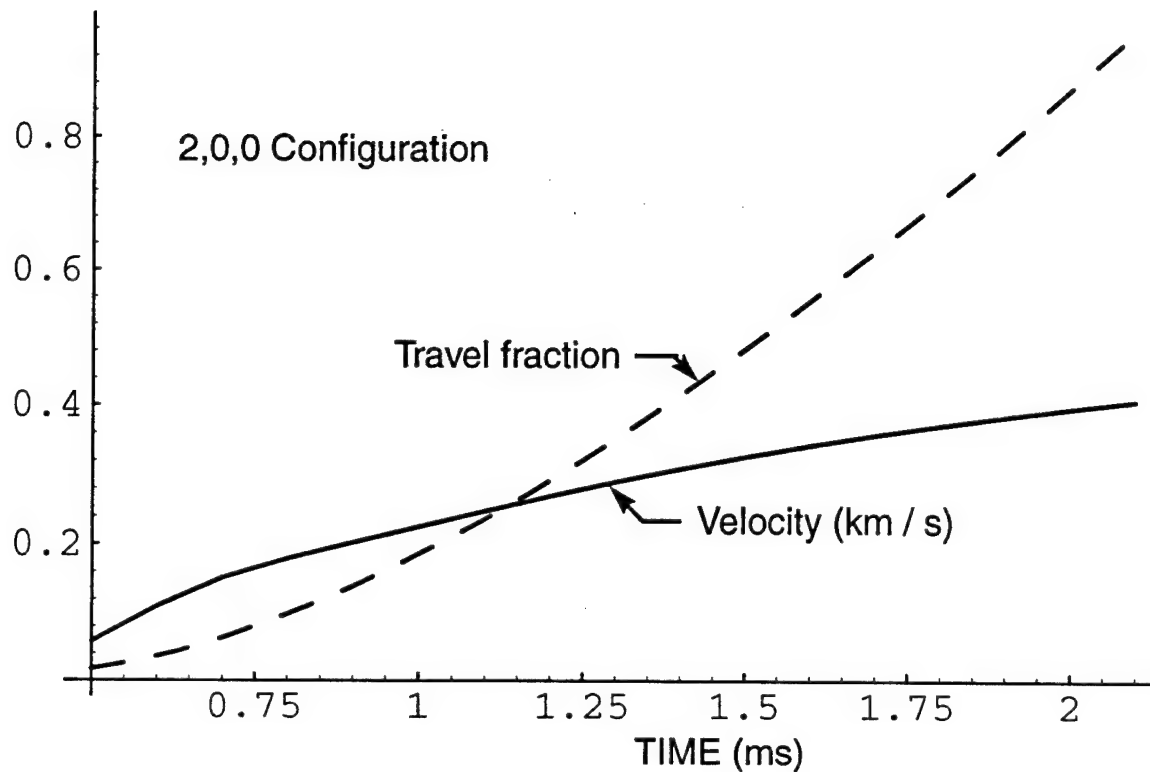


Figure 9. Projectile Velocity and Travel Fraction Versus Time for 2,0,0 Configuration

6. SUMMARY AND CONCLUSIONS

Reducing muzzle velocity to nonlethal levels by venting propellant gas from a gun barrel was investigated. If nonlethal levels could be achieved, a weapon could be designed that would preserve the lethality of today's weapons but could also operate in a nonlethal mode by manipulation of a simple mechanism to control venting.

To investigate this possibility, an interior ballistics lumped parameter code (IBRGA) was modified to simulate venting from the barrel through holes that would instantaneously open after the projectile had traveled a given distance. The simulated results were compared with the classical solution of Corner (1947), which agreed within the approximating assumptions. The modified code was then used to calculate muzzle velocities for a vented M16A2. The venting area could be adjusted to reduce the velocity of a projectile to a nonlethal value if a small enough pre-venting distance was used. However, the round, as designed, does not allow venting to occur for such a short projectile travel distance.

To explore the agreement of the model simulation to the experiment, M16 rifle tubes were

modified to allow the venting of propellant gas. Barrel No. 1 had three rows of four holes drilled around the circumference near but in front of the casing of the chambered round. Barrel No. 2 had three rows of four holes drilled at the same positions as for Barrel No. 1. In addition, three rows of four holes were drilled about 6.5 inches farther up the barrel. A sleeve cylinder held the propellant gases escaping from the vented barrel and allowed the contained gases to be introduced in front of the projectile to increase pressure on the projectile's front surface, with the purpose of decreasing the muzzle velocity.

The tests with the barrels showed that venting could reduce the projectile velocity substantially but vent holes could not be installed close enough to the origin of projectile travel to reduce the velocity of the projectiles to the predicted nonlethal values obtained with the modified IBRGA code. Moreover, attempts to vent propellant gas in front of the projectiles did not yield further noticeable reductions in muzzle velocity.

Although calculations indicate that nonlethal velocities can be obtained by judicious placement of the vents with prescribed area, confirmation by experiment was not achieved. The minimum pre-venting travel was so large for the particular weapon system that nonlethal velocities could not be attained with the conventional propellant. As the bore diameter for the M16 rifle is too small to modify and develop the M16 system into a weapon that can selectively fire rounds at lethal or nonlethal velocities, further studies and development will be conducted with a 50-caliber barrel combined with the M16 receiver that is familiar to the troops.

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LIST OF SYMBOLS

A	area of the bore, m^2
A_v	total venting area, m^2
b	propellant gas co-volume, cm^3/g
C	total mass of propellant charge, kg
d_f	distance between the flats of rolled ball propellant grain, mm
D	propellant web size, cm
E	mean total internal energy of burned fraction of propellant
F	impetus or force, MJ/kg
$H(x - x_o)$	Heaviside step function
m_p	mass of the projectile, kg
P_b	pressure at the base of the projectile, MPa
P_g	pressure of the gas at front of projectile, MPa
P_{peak}	peak mean pressure, MPa
r_b	bore resistance attributable to friction and engraving, MPa
R	average value of gas constant per unit mass for remaining gas, m^2/s^2
T	average value of temperature of remaining gas, K
V_p	muzzle velocity, m/s
x_o	travel fraction when venting is activated
ϵ	$b\rho/(1 - b\rho)$, value in series expression
γ	specific heat ratio
ρ	average density of burnt remaining gas, kg/m^3
ψ	expression involving the specific heat ratio

Ψ

dimensionless parameter used to calculate Corner's solution

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